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A MAGNETOGASDYNAMIC POWER GENERATION STUDY

by

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INTRODUCTION

During the third quarter calculations were carried out of a pre-ionized plasma in a flowing system with finite recombination rates and compared to experimental results obtained with the electron beam. Correlation between theory and experiment was excellent. As well, experiments were conducted with an applied voltage on one pair of the generator electrodes with a flowing system. Voltage-current traces were obtained when the applied electric field was either aided or opposed by a $U \times B$ induced electric field. Some estimates of sheath voltages were obtained, and the characteristics of the body of the ionized plasma could be estimated.

Again, during this quarter a supersonic nozzle and test section were designed, fabricated, and commissioned. Initial experiments were just beginning at the end of the period. Full details will be presented in the summary report.

Finally, a review of the concept of an MHD generator coupled to a space power system has been made. A brief resume of this has been included.

Author

SPACE NUCLEAR POWER AND MHD GENERATORS

Space Power System

Of nuclear space power plants under consideration today the one which can be seriously considered for MHD should have a power level ~ 1 MW (i. e. Snap-50). For systems larger than this it will be even more useful; for smaller systems it will not apply very well. This is due to the increase in volume to surface area ratio as generator size is increased, since heat, friction, and electrode losses all decrease as the generator gets larger.

The basic feature to be aware of from the space power systems point of view is that the plasma MHD generator replaces the turbine and alternator in the Rankine cycle and the remainder of the system is unchanged. (See Figure 1 for example). In precisely the same way, one can consider an MHD generator used with a Brayton cycle.

Realistic calculations of Snap-50 Rankine cycle efficiency yield figures on the order of 15% using turbo-electric conversion gear. Similar realistic calculations using a liquid MHD generator show efficiencies of approximately 5-6%. When a plasma MHD generator is considered such realistic calculations are not possible as there are many research questions still unanswered about their performance. Presently possible ideal calculations, however, show that the plasma MHD generator should be as efficient as the turbo-electric conversion gear. If this can be verified in our present research studies, we can again anticipate a system efficiency of 15%. Such a possibility for high system efficiency does not exist for the liquid MHD generator as the MHD portion of this system is reasonably well understood.

In either case the overall system is now simpler, more reliable, and should be able to operate for very long times (i. e., several years). Also, if higher reactor temperatures become possible the MHD generator

operation becomes simpler if anything.

As well as system efficiency, weight is a proper consideration for a space power plant, and one must consider methods of creating the desired magnetic fields. By use of a superconducting magnet and liquid H_2 boil off an MHD generator + magnet unit can be built to weigh approximately 2#/KW for a one megawatt system, which is essentially the same as the weight of a comparable turbo-alternator. An approximate evaluation of this point has been included in the following discussion.

Finally, power conditioning is of importance. Typically, the plasma MHD generator will generate D. C. voltages on the order of hundreds of volts, and for certain generator geometries may generate several kilovolts. For plasma or ion propulsion power conditioning equipment should be unnecessary. If A. C. is needed, inverters will be necessary.

The Plasma MHD Generator

Considering the ultimate application for which the plasma MHD generator is intended some comments can be made regarding operating conditions. Generally, a low pressure and a high temperature are desirable in order to maximize non-equilibrium ionization. The former must probably not go below one atmosphere or the entire system becomes too voluminous, while reactor temperatures will limit the latter to 2000°F for the Rankine cycle systems and 3500°F for the Brayton cycle systems. For the metal vapor system some superheat will be necessary to prevent liquid metal layers from forming on insulator walls. How much, will depend on the influence of droplets on non-equilibrium ionization, and initial theoretical studies of this question have been made.

Clearly non-equilibrium ionization is the key element in the plasma MHD generator for a space nuclear system. Since the General Electric Space Sciences Laboratory has been investigating non-equilibrium ionization in plasmas since 1959 a summary of previous studies may be

useful.

1959 Theoretical predictions by Hurwitz, Sutton

1960 Diode experiments in $H_e + C_s$

1962 Flowing experiments in A + K - Arc heater

Based on these experimental and theoretical studies several additional experiments were designed, and these have yielded significant new results. The first of these was a shock tube study sponsored by ONR. The test set up is shown in figures 2 and 3. The objective here is to have a high purity system (polyatomic species quench non-equilibrium ionization), and a very high magnetic field in order to produce very high magnetically induced voltages. In late 1963 we were able to demonstrate in this experiment that magnetically induced non-equilibrium ionization was indeed possible. In these experiments Xenon was raised to 5000°K in order to simulate the degree of ionization that one would achieve at much lower temperatures in a seeded gas. The pressure was essentially atmospheric and the velocity slightly supersonic, $M \cong 1.5$. Some typical experimental results showing an order of magnitude or more increase in electrical conductivity are shown on the following page. Hall voltages on the order of several hundred volts have already been generated in this experiment.

Shortly after the shock tube experiment was started, another experiment with longer testing time was begun. Here, since we felt that temperatures less than 3000°F would be of interest, an ARC heater was ruled out and an electrical resistance heater was selected. At the present time we heat Argon up to 2200°F at a mass flow rate of 0.30#/sec. and several atmospheres pressure. This flow is then seeded with a small quantity of cesium, and then subjected to an ionizing electron beam. The beam operates at 50,000 volts and is capable of 40 m.a. of current.

This experiment is presently the one being studied under the present NASA contract.

Finally, we have also been interested in studying the plasma MHD

SUMMARY

1) EXPERIMENTAL OBSERVATION OF MAGNETICALLY INDUCED IONIZATION:

$$\frac{n_e}{(n_e)_0} \sim 4 \text{ to } 8, \frac{\sigma}{\sigma_0} \sim 4 \text{ at } 3 \text{ W/m}^2.$$

2) OPERATION OF HALL GENERATOR WITH NON-THERMAL MAGNETICALLY INDUCED IONIZATION:

$$\sigma_{\text{initial}} \cong 100 \text{ Mhos/m, } B = 3 \text{ Wm}^2$$

Max. Power - 15KW

Max. Hall Voltage - 350V

Max. Hall Current - 135 Amp

UB - 3000 V/m

3) LARGE ELECTRODE VOLTAGE LOSSES

$$\text{FOR CURRENT/ELECTRODE} \sim 1\text{A; } 40\% < \frac{V_s}{UB_d} < 100\%$$

$$\text{FOR CURRENT/ELECTRODE} \sim 200\text{A; } \frac{V_s}{UB_d} \sim 40\%$$

4) LOW MEASURED HALL VOLTAGE DUE TO SHORTING DOWNSTREAM OF GENERATOR.

generator when a metal vapor is to be used as the working fluid. The obvious difficulty is creating a high mass flow stream of a high temperature corrosive vapor such as Potassium. Toward this end we have conceived two separate experiments.

In the first, we propose to run a short time blowdown experiment (~ 10 seconds) using a Potassium boiler (1500^oF, 24 psia) with perhaps several pounds of Potassium. A condensor serves as a vacuum pump. Testing time is limited by the quantity of Potassium used. In order to make the experiment one of maximum experimental convenience no recovery or purification of the Potassium will be attempted. Also, to allow for a range of different experimental conditions a superheater capable of raising the vapor temperature to 2000^oF will be installed directly after the boiler. Despite the short operating time available, this experiment will permit rapid changes in the MHD generator configuration as well as easier application of necessary diagnostic techniques. Initial operation of the system has proceeded as planned.

For longer tests in pure metal vapors we have constructed a complete, recirculating, Potassium loop. Here in addition to the same components as in the blowdown we have an electromagnetic pump along with a complete purification loop (hot and cold traps) which circulates 90% of the mass flow at all times. Again, operation of this loop has been as designed.

Magnetic Field Generation

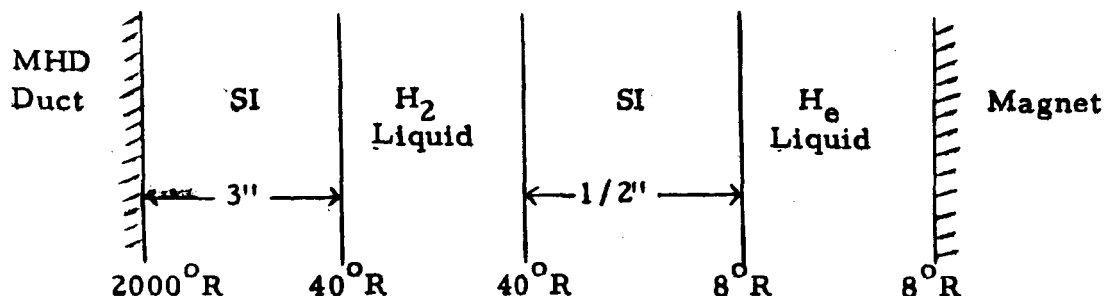
Despite the possibilities of using self-excited coils or permanent magnets under certain optimistic assumptions, we feel that the superconducting coil is the only proper approach to generating the magnetic field needed. In general a high field strength (> 50,000 gauss) will be needed for efficient generator operation, and the superconducting magnet is the only way to get field strengths this high with little if any penalty in power consumed or weight added.

To date experience with superconducting wire and coils has demonstrated the potential of going to 200,000 gauss some day in a superconducting solenoid. So far, small solenoids have been operated over 100,000 gauss (101,000 gauss at GE, 107,000 gauss at RCA). In larger coils a degradation of critical current density has been observed so that fields less than 50,000 gauss have been created in the larger sizes. In one 18" I. D. coil supplied to Argonne National Laboratory approximately 36,000 gauss was achieved. This size is of the same order as one might contemplate needing for a 1 Megawatt space power system. Also, since a Niobium-Zirconium wire was used, one can anticipate considerably higher fields with the higher critical current capability of the Niobium-Tin wire currently available. This difference in critical current capability is shown in the accompanying figure.

As for coil configuration a simple split coil would be possible. Calculations have been made for such a superconducting coil in order to establish feasible sizes, field strengths, etc. One such coil is also shown.

A critical question relates to the problem of cooling such a coil. If the heat input is too high a very large, heavy, and complicated cryostat would be needed. Alternately, the weight of liquid H_e to be boiled away over a year's time would be enormous. A sample calculation has been made to explore this question.

Using Linde super insulation and a blanket of H_2 liquid we can estimate the heat flux between a $2000^{\circ}R$ wall and a liquid H_e temperature wall.



For a heat transfer area of 10 ft.^2 and a $1/2''$ thick layer of insulation between H_2 and H_e liquids we have

$$\dot{q} = \frac{k A \Delta T}{L} = 4.8 \times 10^{-2} \text{ Btu/hr.} \cong 480 \text{ Btu/year}$$

with $k = 6 \times 10^{-6} \text{ Btu/hr. ft. } ^\circ\text{R}$ between 40°R and 530°R . Then

$$M = \frac{480 \text{ Btu/year}}{8.8 \text{ Btu/\#}} \cong 50 \text{ lbs./year}$$

A similar calculation for heat flux between the hot wall and the liquid H_2 with a $3''$ thick insulator and 1 ft.^2 area gives

$$\dot{q} = 4 \times 10^4 \text{ Btu/year}$$

with $k = 0.48 \times 10^{-3} \text{ Btu/hr. ft. } ^\circ\text{R}$ between 40°R and 2000°R . Then

$$M = \frac{4 \times 10^4}{193} \cong 200 \text{ lbs/year}$$

The remainder of the magnet not near the hot zone will transfer heat in from 530°R to 40°R liquid H_2 . Then with $k = 2 \times 10^{-5} \text{ Btu/hr. ft. } ^\circ\text{R}$, $A = 10 \text{ ft.}^2$, and a $3''$ thick layer we have

$$\dot{q} = 4000 \text{ Btu/year}$$

and

$$M \cong 20 \text{ lbs/year}$$

The total weight penalty if we allow boil off to remove the heat flux is $\sim 300 \text{ lbs.}$ for a 1 year mission. The contemplated one M. W. space nuclear system will weigh $\sim 300 \text{ lbs.}$ ($30\#/\text{KW}$), so the above represents only 1% of the system mass.

To estimate generator weight we need only note that if we can achieve plasma electrical conductivities of 10 mhos/meter at reasonable gas temperatures (we already have measured 10 mhos/meter at 2200°F) then generator power densities of $\sim 10 \text{ MW/meter}^3$ are feasible. Such a generator is quite compact and should weigh $\sim 300 \text{ lbs.}$ at most. Summing then

Generator	300 lbs.
Coil + Structure	700 lbs.
Boil Off	<u>300 lbs.</u>
	1300 lbs.

Allowing for the approximate nature of the estimate we might say 2000 lbs. For the 1 MW system this adds 2# KW while replacing the turbo-alternator.

These evaluations are, of course, very approximate and neglect several factors. Despite this they are sufficiently encouraging to warrant further study of the plasma MHD generator system. This is especially true since such a system if successful would permit the same system weights and efficiencies as are contemplated in the present Snap-50 program, and would offer much greater simplicity and reliability than the turbo-machinery conversion gear being considered.

MHD Flows in a Recombining Plasma

In the previous quarterly report experimental data of pre-ionization with an electron beam were reported. The surprising feature of these measurements was the slow decay of the ionization created by the beam. To explore the question further a theoretical analysis developed under an AFOSR program was applied to the experimental measurements. Essential to the analysis is the inclusion of finite rate processes in the flow problem while still accounting for non-equilibrium ionization. To start with we have the usual one-dimensional MHD flow equations.

$$\rho u A = c \quad (1)$$

$$\rho u \frac{du}{dx} + \frac{dp}{dx} = (\bar{j} \times \bar{B})_x \quad (2)$$

$$\rho u \frac{d}{dx} \left[C_p T + \frac{u^2}{2} \right] = \bar{j} \cdot \bar{E} \quad (3)$$

$$p = \rho R T \quad (4)$$

$$j_x = \frac{\sigma}{1+\beta^2} [E_x - \beta (E_y - u B)] \quad (5)$$

$$j_y = \frac{\sigma}{1+\beta^2} [E_y - u B + \beta E_x] \quad (6)$$

Instead of the usual assumption of $\sigma = \text{const.}$ we write it in its defined form

$$\sigma = \frac{n_e e^2}{m_e \nu} \quad (7)$$

The equation for the electron density is given by the rate equation

$$\frac{d}{dx} [n_e u_e] = -n_e^3 \nu_{r3} + n_e n_s \nu_{i3} - n_e^2 \nu_{r2} + n_p n_s \nu_{i2} \quad (8)$$

where the first 2 terms represent 3 body recombination and ionization and the last 2 terms represent 2 body recombination and ionization.

ν_{r3} is determined as a function of electron temperature from the work of ³J. V. Dugan (Three-Body Collisional Recombination of Cesium Seed Ions and Electrons in High-Density Plasmas with Argon Carrier Gas, NASA TN D-2004). ν_{r2} as a function of electron temperature is estimated from the work of Dr. ² Bates (Atoms and Molecular Processes, Academic Press, New York and London, pg. 252, 1962). In order that thermodynamic equilibrium can be achieved ν_{i3} are determined by the method of detailed balance so that equation (8) takes the form

$$\begin{aligned}
\frac{d}{dx} n_e u_e &= - \left[1 - \frac{n_s - n_e}{n_e^2} \left(\frac{u_e^2}{n_s - n_e} \right)_{eq} \right] n_e^3 \nu_{n_3} \\
&\quad - \left[1 - \frac{n_s - n_e}{n_e^2} \left(\frac{u_e^2}{n_s - n_e} \right)_{eq} \right] n_e^2 \nu_{n_2} \\
&\equiv \frac{d}{dx} n_e u_e \Big|_3 + \frac{d}{dx} n_e u_e \Big|_2
\end{aligned} \tag{9}$$

where:

$$\left(\frac{u_e^2}{n_s - n_e} \right)_{eq} = \left(\frac{2\pi m k T_e}{h^2} \right)^{3/2} \exp \left(-\frac{e \phi_i}{k T_e} \right) \tag{10}$$

$$\nu_{n_3} = \frac{2.3 \times 10^7}{T_e^5} \quad \left. \vphantom{\frac{2.3 \times 10^7}{T_e^5}} \right\} \text{ for Cesium} \tag{11}$$

$$\nu_{n_2} = \frac{1.44 \times 10^{-10}}{T_e^{0.7}} \tag{12}$$

The electron temperature is determined from the electron energy equation

$$\begin{aligned}
n_e u_e \frac{d}{dx} \left[\frac{5}{2} k T_e + \frac{u_e^2}{2} \right] &= \bar{j} \cdot [\bar{E} + \bar{v} \times \bar{B}] \\
&\quad - \sum_j n_e \nu_{ej} \left(2 \delta_j \frac{m}{M_j} \right) \frac{3}{2} k (T_e - T) \\
&\quad + \left(\epsilon_i + \frac{5}{2} k T_e + \frac{u_e^2}{2} \right) \frac{d}{dx} n_e u_e \Big|_3
\end{aligned} \tag{13}$$

where only 3 body term is included in last term since radiative term does not effect electron energy. The collision frequencies ν_{ej} are

$$\nu_{ea} = n_a Q_{ea} \left(\frac{8 k T_e}{\pi m} \right)^{1/2} \tag{14}$$

$$V_{ei} = n_e \frac{16\sqrt{\pi}}{3} \left(\frac{e^2}{m}\right)^2 \left(\frac{2kT_e}{m}\right)^{-3/2} \ln \frac{3}{2} \frac{1}{e^3} \left(\frac{kT_e}{\pi n_e}\right)^{1/2} \quad (15)$$

$$V_{es} = n_s Q_{es} \left(\frac{\delta kT_e}{\pi m}\right)^{1/2} \quad (16)$$

The above set of equations are still indeterminate to the extent that the channel configuration, i.e., $A(X)$, is under the control of the experimenter. For the sake of simplicity we therefore choose A to be such that $U = U_0 = \text{const.}$ and further restrict ourselves to the segmented electrode case, i.e.,

$$j_x = 0 \quad E_x = \beta(E_y - uB) \quad (17)$$

$$\therefore j_y = \sigma[E_y - uB] \quad (18)$$

Then defining $E_y = K u B$ (19)

$$j_y = -\sigma(1-K)uB \quad (20)$$

and $u_e = u_0$ (21)

The the equations governing the flow reduce to

$$\rho A = \rho_0 A_0 \quad (22)$$

$$\frac{dp}{dx} = j_x B = -\sigma(1-K)u_0 B^2 \quad (23)$$

$$\rho u_0 \frac{d}{dx} \frac{5}{2} kT = -\sigma(1-K)/K u_0^2 B^2 \quad (24)$$

$$j = \rho R T \quad (25)$$

$$\sigma = \frac{n_e e^2}{m \nu} \quad (26)$$

$$\frac{d}{dx} n_e = - \left[1 - \frac{n_s - n_e}{n_e} \left(\frac{n_e^2}{n_s - n_e} \right)_{eq} \right] \frac{n_e^3 v_r}{u_0} \quad (27)$$

$$n_e u_0 \frac{d}{dx} \frac{5}{2} k T_e = \sigma [1 - K]^2 u_0^2 B^2 - \sum_i n_e v_{ei} \left(2 \delta_i \frac{m}{m_i} \right)^{\frac{3}{2}} k (T_e - T) - \left(\epsilon_i + \frac{5}{2} k T_e + \frac{u_0^2}{2} \right) \frac{d}{dx} (n_e u_0) \quad (28)$$

Equations 23-25 can be solved so that equation (24) can be replaced

$$\frac{T}{T_0} = \left(\frac{p}{p_0} \right)^{\frac{K(\gamma-1)}{\gamma}} \quad (29)$$

where

$$\gamma = c_p / c_v \quad (30)$$

The seed density n_s is given by

$$n_s = (\% \text{ seed}) n_a \equiv \alpha n_a \quad (31)$$

$$n_a \approx \frac{p}{kT} \quad (32)$$

We now solve equations 23, 26, 14-16, 29, 27, 10, 11, 31, 32, and 28 to determine T , p , σ , T_e , and n_e as a function of distance down the channel for various initial conditions.

Carrying out the indicated calculations for one of the experimental measurements reported previously resulted in the T_e and n_e profiles along the channel shown in Figure 4. The principle conclusion possible is that due to the relatively low electron density ($n_e \sim 3 \times 10^{12}/\text{cc}$) the rate of loss of electrons is quite slow. As well, the electron temperature drops to a value close to the gas temperature very quickly.

Non-equilibrium Ionization with Magnetic Fields

Preliminary to proper generating experiments some experiments were under taken with a single pair of electrodes and an applied electric

electric field. To help distinguish differences between an applied or an induced electric field a magnetic field was applied and the applied electric field was reversed in direction. Some typical and preliminary measurements are shown in Figure 5. From this data it appears as if there is a (sheath) voltage at which current begins to flow. Then as voltage increases the current does so as well linearly for an initial portion. This may correspond to an equilibrium electrical conductivity region. As the voltage is increased further the current becomes non-linear presumably due to non-equilibrium ionization. An increase in gas temperature in the region of the discharge can be discounted since the $j \cdot E$ energy addition is small compared to the flow enthalpy.

The lower voltage necessary to pass a given current when a magnetic field is applied in the appropriate direction can perhaps be attributed to the adding of the $U \times B$ induced voltage in the plasma to the applied electric field. However, uBl should have been 27 volts while the difference measured was on the order of 5 volts. Further measurements will be necessary to clarify this discrepancy.

Nonetheless if we make the tentative assumption that the sheath drop is constant (at 9 and 14 volts respectively) we can derive conductivity values from the data of Figure 5 and these are shown in Figure 6. First, it should be noted that σ as derived for Figure 6 should properly be $\sigma_0 / 1 + (\omega\tau)^2$ where σ_0 is the scalar conductivity, since we only used a single electrode pair. Thus, some very high conductivities were measured.

In principle, both sets of measurements in figure 6 should coincide. The differences observed are not large, but one reason for them may be the lack of a constant sheath voltage. One in fact would expect the sheath drop to vary with current.

Finally, it must be noted that visual observation of the discharge region showed a uniform, diffuse, discharge. No streamers, spokes, or arcs were observed.

CONCEPTUAL DESIGN OF MHD SODIUM VAPOR CYCLE

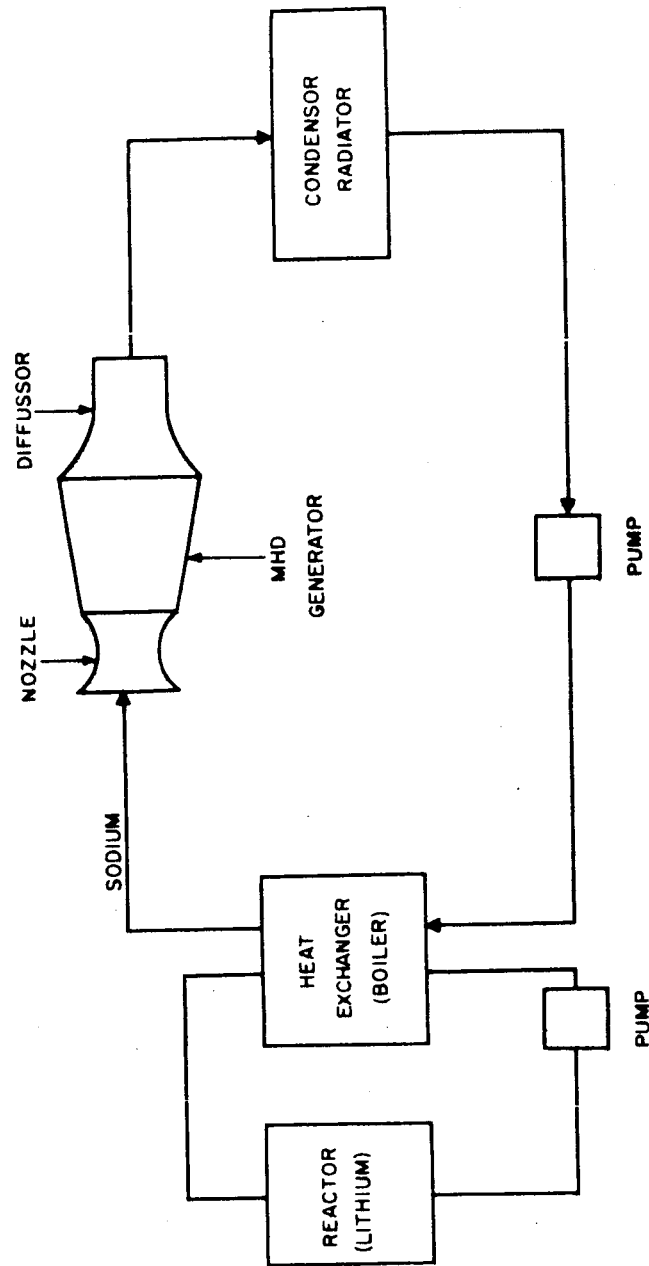
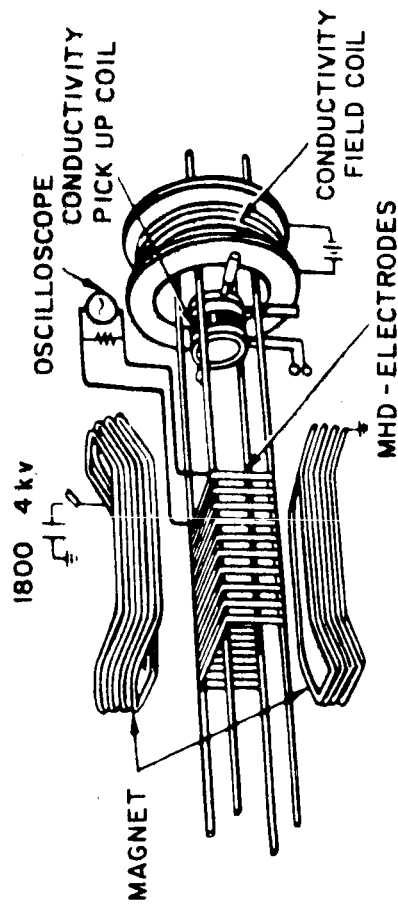
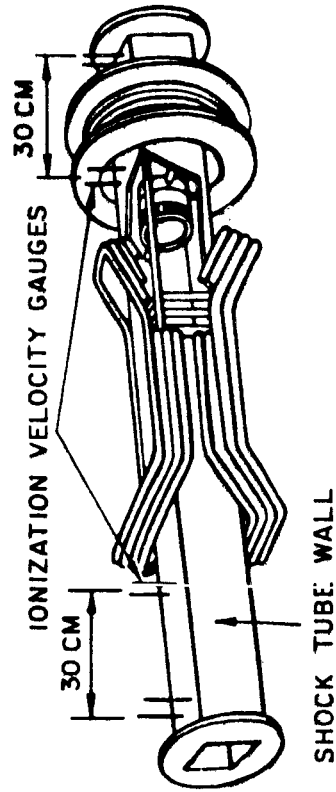


FIGURE 1



INTERNAL VIEW OF PROTRUDING
ELECTRODE ASSEMBLY INCLUDING
EXPLODED VIEW OF MHD FIELD
MAGNET AND DOWN-STREAM
CONDUCTIVITY PROBE



EXTERNAL VIEW OF PROTRUDING
ELECTRODE MHD TEST CHANNEL

FIGURE 2

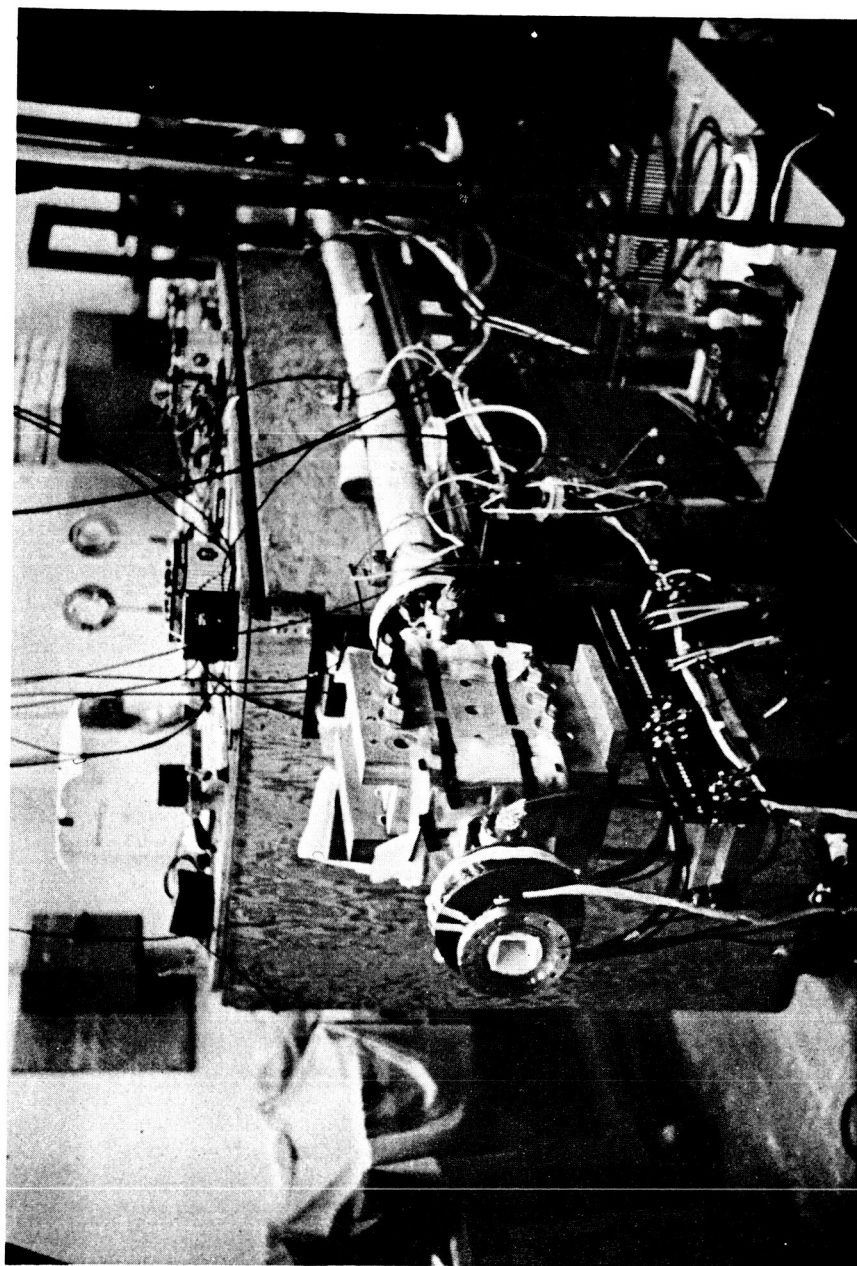


FIGURE 3

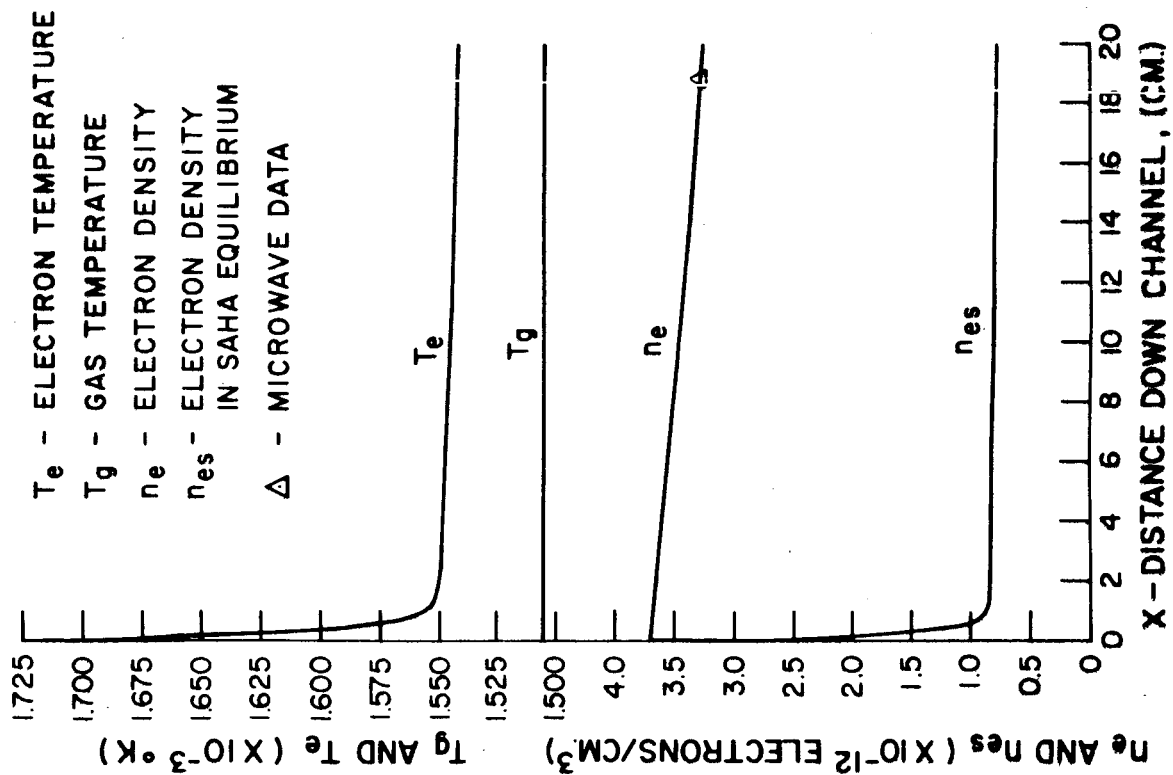


FIGURE 4

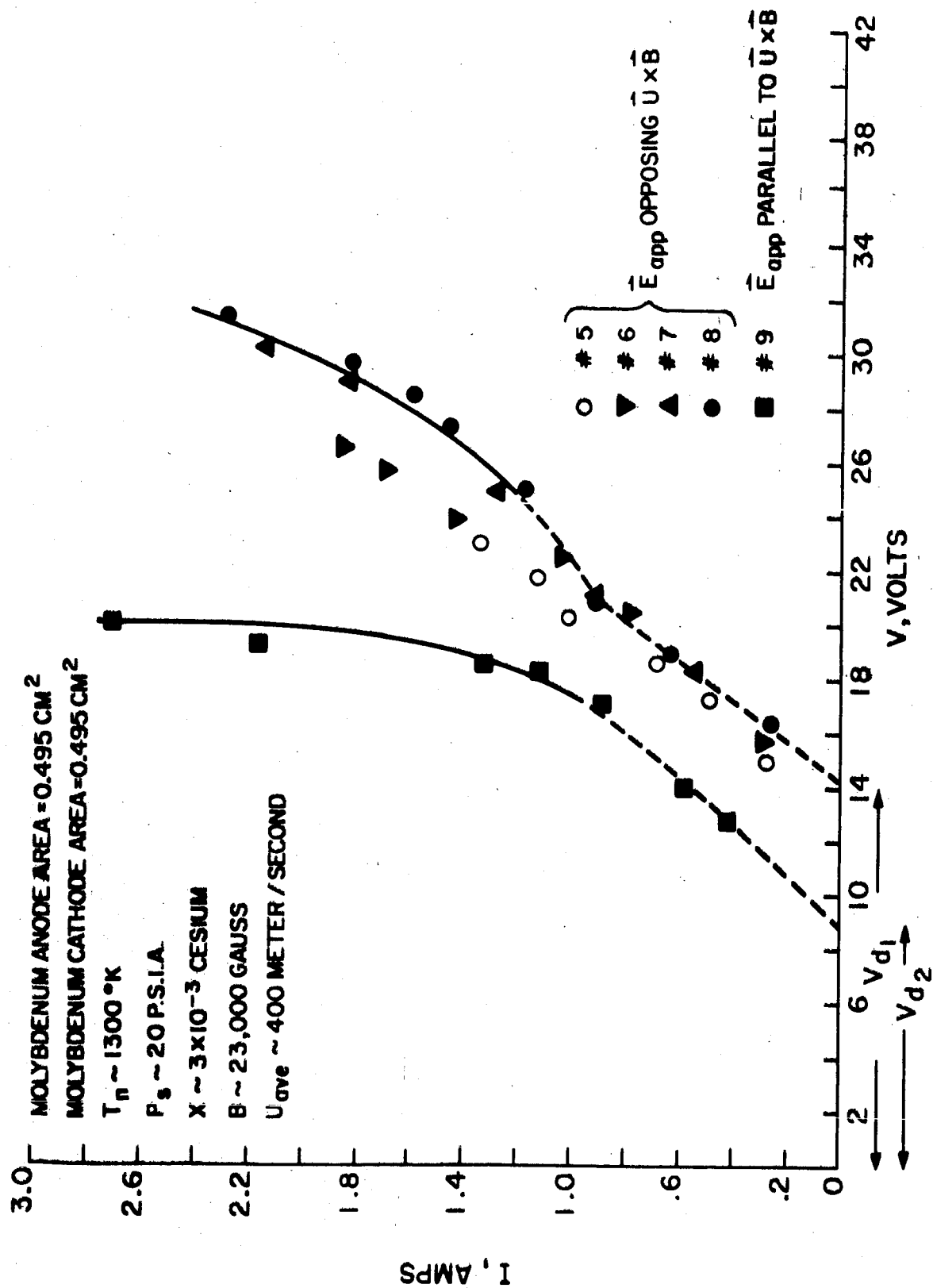


Figure 5

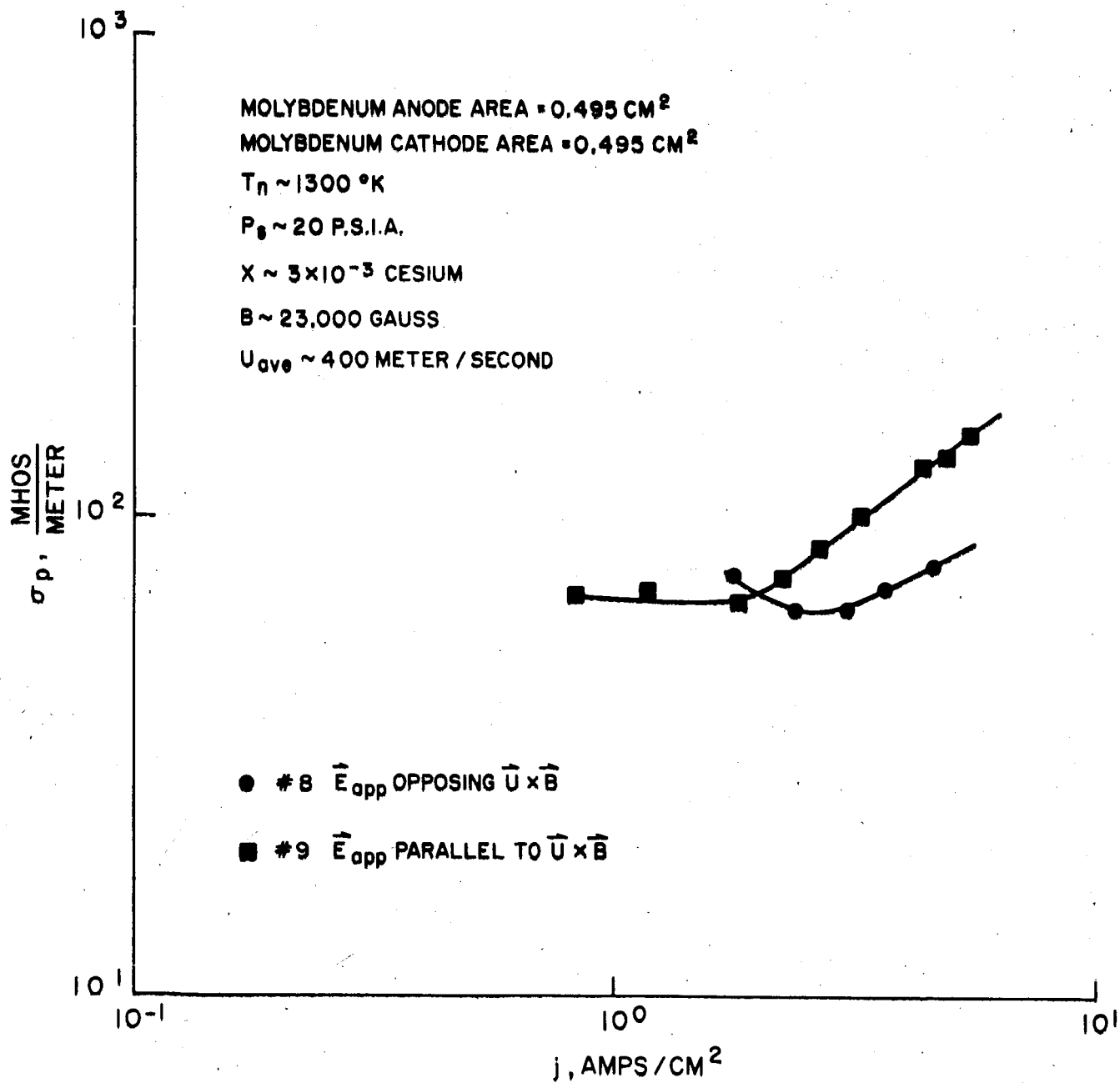


Figure 6.